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Origin of the Galactic Halo: accretion vs. in situ formation

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Abstract. We test the hypothesis that the classical and ultra-faint dwarf spheroidal satellites of the our Galaxy have been the building blocks of the Galactic halo by comparing their [O/Fe] and [Ba/Fe] vs. [Fe/H] patterns with the ones observed in Galactic halo stars. The [O/Fe] ratio deviates substantially from the observed abundance ratios in the Galactic halo stars for [Fe/H] > -2 dex, while they overlap for lower metallicities. On the other hand, for the neutron capture elements, the discrepancy is extended at all the metallicities, suggesting that the majority of stars in the halo are likely to have been formed in situ. We present the results for a model considering the effects of an enriched gas stripped from dwarf satellites on the chemical evolution of the Galactic halo. We find that the resulting chemical abundances of the halo stars depend on the adopted infall time-scale, and the presence of a threshold in the gas for star formation.

Keywords. ISM: abundances - Galaxy: abundances - Galaxy: evolution - Galaxy: halo.

1. Introduction

The ΛCDM paradigm predicts that a Milky Way-like galaxy must have formed by the assemblage of a large number of smaller systems. In particular, dwarf spheroidal galaxies (dSphs) were proposed in the past as the best candidate small progenitor objects, which merged through cosmic time to eventually give rise to the stellar Galactic halo (e.g. Grebel 2005). On the other hand, Fiorentino *et al.* (2015) using RR Lyrae stars as tracers of the Galactic halo (GH) ancient stellar component, showed that dSphs do not appear to be the major building-blocks of the GH, estimating an extreme upper limit of 50% to their contribution. The SDSS (York *et al.* 2000) discovered a new class of objects characterized by extremely low luminosities, high dark matter content, and very old and iron-poor stellar populations: the ultra faint dwarf spheroidal galaxies (UfDs). In Spitoni *et al.* (2016) we test the hypothesis that dSph and UfD galaxies have been the building blocks of the GH, by assuming that the halo formed by accretion of stars belonging to these galaxies. Moreover, extending the results of Spitoni (2015) to detailed chemical evolution models in which the IRA is relaxed, we explored the scenario, in which the GH formed by accretion of chemically enriched gas originating from dSph and UfD galaxies.

2. The chemical evolution models

For the Milky Way we consider the following two reference chemical evolution models:

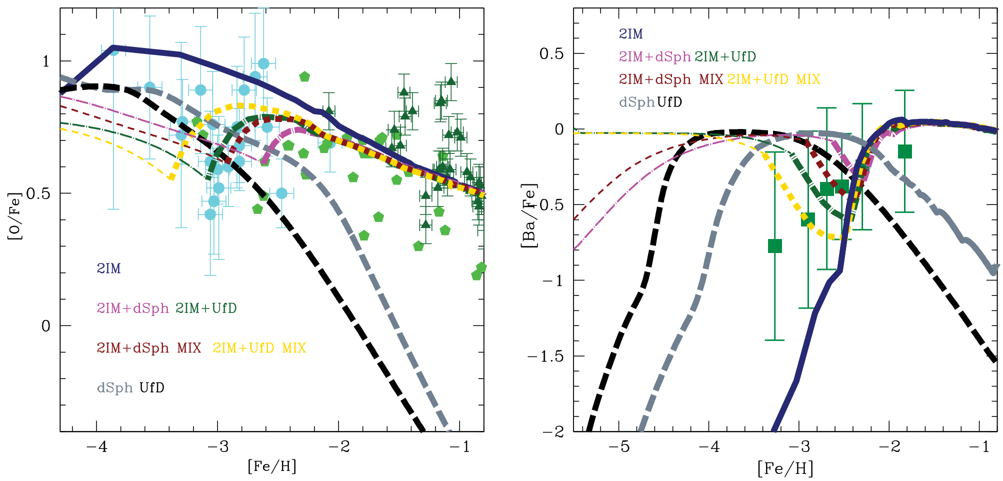

Figure 1. [O/Fe] vs [Fe/H] (left panel) and [Be/Fe] vs [Fe/H] (right panel) ratios in the GH in the solar neighborhood for the reference model 2IM are drawn with the solid blue line. *Models with the enriched infall from dSph*: the magenta dashed dotted line and the red short dashed line represent the models 2IM+dSph and 2IM+dSph MIX, respectively. *Models with the enriched infall from UfDs*: the green dashed dotted line and the yellow short dashed line represent the models 2IM+UfD and 2IM+UfD MIX, respectively. Thinner lines indicate the ISM chemical evolution phases in which the SFR did not start yet in the GH, and during which stars are no created. *Models of the dSph and UfD galaxies*: The long dashed gray line represents the abundance ratios for the dSph galaxies, whereas long dashed black line for the UfD galaxies. *Observational O data of the GH:* Cayrel *et al.* (2004) (cyan circles), Akerman *et al.* (2004) (light green pentagons), Gratton et al. (2003) (dark green triangles). *Ba data of the GH:* Frebel (2010).

(a) The classical two-infall model of Chiappini *et al.* (1997) updated by Brusadin *et al.* (2013) (model 2IM). The Galaxy is assumed to have formed by means of two main infall episodes: the first formed the halo and the thick disk (with an infall time scale $\tau_H = 0.8$ Gyr), the second one the thin disc ($\tau_D = 7$ Gyr, in the solar neighborhood).

(b) The two-infall model plus outflow of Brusadin *et al.* (2013; here we indicate it as the 2IMW model) with $\tau_H = 0.2$ Gyr. In this model a gas outflow occurring during the GH with a rate proportional to the SFR through a free parameter is considered.

In Tables 1, 2, and 3 of Spitoni *et al.* (2016) all the adopted parameters of the Milky Way, dSph and UfD models are reported. Here, we only underline that UfDs are characterized by a very small star formation efficiency (SFE) (0.01 Gyr^{-1}) and by an extremely short time scale of formation (0.001 Gyr). The time at which the galactic wind starts in dSphs is at 0.013 Gyr after the galactic formation, whereas for UfDs at 0.088 Gyr. As expected, the UfD galaxies develop a wind at later times because of the smaller adopted SFE. The nucleosynthesis prescriptions are the ones of Romano *et al.* (2010, model 15) and for Ba, the ones of Cescutti *et al.* (2006, model 1). Concerning the model for the GH with the enriched infall we assume that the gas infall law is the same as in the 2IM or 2IMW models and it is only considered a time dependent chemical composition of the infall gas mass. We tested two different models:

• Model i): The infall of gas which forms the GH is considered primordial up to the time at which the galactic wind in dSphs (or UfDs) starts. After this moment, the infalling gas presents the chemical abundances of the wind. In Figs. 1 and 2 we refer to this model with the label “2IM(W)+dSph”or “2IM(W)+UfD”.

• Model ii): we explore the case of a diluted infall of for the GH. In particular, after the galactic wind develops in the dSph (or UfD) galaxy, the infalling gas has a chemical

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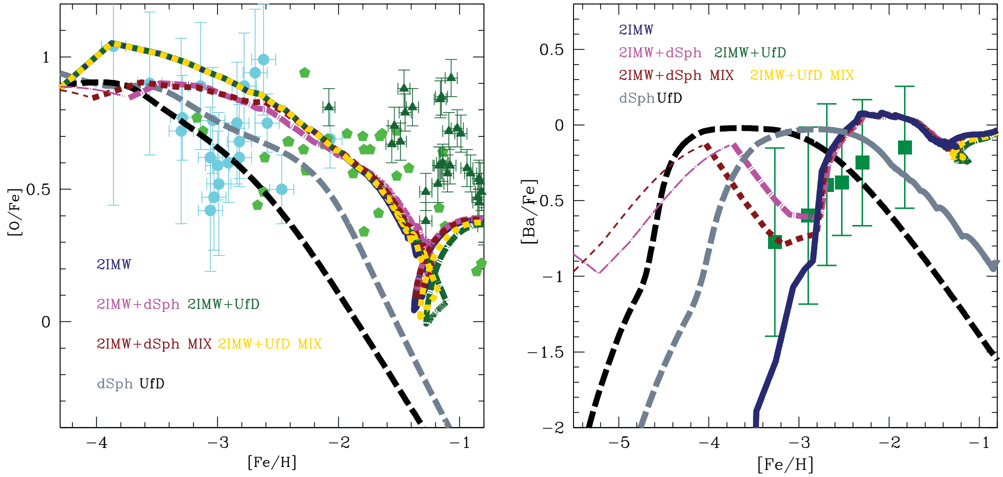

Figure 2. As in Fig. 1 but for the 2IMW model.

composition which, by 50 per cent, is contributed by the dSph (or UfD) outflows; the remaining 50 per cent is contributed by primordial gas of a different extra-galactic origin. In all the successive figures and in the text, we refer to these models with the labels "2IM(W)+dSph(UfD) MIX".

3. The Results

3.1. *The Results: the Galactic halo in the model 2IM*

In order to directly test the hypothesis that GH stars have been stripped from dSph or UfD systems, in the left panel of Fig. 1, the predicted [O/Fe] vs. [Fe/H] abundance patterns for typical dSph and UfD galaxies are compared with the observed data in GH stars. The two models cannot explain the [O/Fe] plateau which GH stars exhibit for [Fe/H] $\geqslant -2.0$ dex. Moreover, in left panel of Fig. 1 we also show the results with the enriched infall coming from dSph galaxies. We recall that a key ingredient of the 2IM model is the presence of a threshold in the gas density in the star formation (SF) fixed at 4 $M_\odot$ pc^{-2} in the GH. Such a critical threshold is reached only at $t = 0.356$ Gyr from the Galaxy formation. During the first 0.356 Gyr in both "2IM+dSph" and "2IM+dSph MIX" models, no stars are created, and the chemical evolution is traced by the gas accretion. After the SF takes over, [O/Fe] values increase because of the pollution from massive stars on short time-scales. In the "2IM+dSph" model the first stars that are formed have [Fe/H] $>$ -2.4 dex. In this case, to explain data for stars with [Fe/H] $<$ -2.4 dex we need stars formed in dSph systems. Concerning the results with the enriched infall from UfD outflow abundances, model results for the GH still reproduce the data but with the same above mentioned caveat. In the right panel of Fig. 1, we show the results for the [Ba/Fe] vs. [Fe/H] abundance diagram. Chemical evolution models for dSphs and UfDs fail in reproducing the observed data, since they predict the [Ba/Fe] ratios to increase at much lower [Fe/H] abundances than the observed data. That is due to the very low SFEs assumed for dSphs and UfDs. The subsequent decrease of the [Ba/Fe] ratios is due to the large iron content deposited by Type Ia SNe in the ISM, which happens at still very low [Fe/H] abundances in dSphs and UfDs. In the right panel of Fig. 1, all our models involving an enriched infall from dSphs and UfDs deviate substantially from the observed trend of the [Ba/Fe] vs. [Fe/H] abundance pattern in GH stars.

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3.2. *The Results: the Galactic halo in the model 2IMW*

In the reference model 2IMW the SFR starts at 0.05 Gyr. Comparing model “2IMW+dSph” in the left panel of Fig. 2 with model “2IM+dSph” in the left panel of Fig. 1, we can see that the former shows a shorter phase with the enriched infall of gas with SF not yet active than the latter. The model results for the model “2IMW+UfD” in the left panel of Fig. 2 overlap to the reference model 2IMW at almost all [Fe/H] abundances. Since in the UfD galactic model the wind starts at 0.088 Gyr and, at this instant, in the model 2IMW the SF is already active. Concerning the [Ba/Fe] vs [Fe/H] ratios (right panel in Fig. 2), we notice that the 2IMW model provides now a better agreement with the observed data than the 2IM model. By assuming an enriched infall from dSph or UfD galaxies, the predicted [Ba/Fe] ratios agree with the observed data also at [Fe/H] < -3 dex.

4. Conclusions

(*a*) The predicted [O/Fe] vs.[Fe/H] abundance ratios of UfD and dSph chemical evolution models deviate substantially from the observed data of the GH stars only for [Fe/H] > -2 dex; we conclude that an evolution in situ in the GH is requested. On the other hand, we notice that for Ba the chemical evolution models of dSphs and UfDs fail to reproduce the observational observed data of the GH stars over the whole range of [Fe/H].

(*b*) The effects of the enriched infall on the [O/Fe] vs. [Fe/H] plots depend on the infall timescale of the GH and the presence of a gas threshold in the SF. The most evident effects are present for the model 2IM, characterized by the longest time scale of formation (0.8 Gyr), and the longest period without SF activity among all models presented here.

(*c*) In the presence of an enriched infall of gas we need stars produced in dSphs or UfD s and accreted later to the GH, to explain the data at lowest [Fe/H].

(*d*) The optimal element to test different theories of halo formation is Ba which is easily measured in low-metallicity stars. In fact, we have shown that the predicted [Ba/Fe] vs. [Fe/H] relation in dSphs and UfDs is quite different than in the GH.

Acknowledgments

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